

# MINIMAL ELECTROWEAK SYMMETRY BREAKING MODEL IN EXTRA DIMENSIONS

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We show that if the Standard Model gauge fields and fermions propagate in extra dimensions, a composite Higgs field with the correct quantum number can arise naturally as a bound state due to the strong gauge interactions in higher dimensions. The top quark mass and the Higgs mass can be predicted from the infrared fixed points of the renormalization group equations. The top quark mass is in good agreement with the experimental value, and the Higgs boson mass is predicted to be  $\sim 200\text{GeV}$ . There may be some other light bound states which could be observed at upcoming collider experiments.

The origin of the electroweak symmetry breaking (EWSB) is currently one of the most important questions in particle physics. In the Standard Model (SM), it is achieved by a nonzero vacuum expectation value of a fundamental scalar Higgs field. However, this picture is not totally satisfactory: there is no understanding of the gauge quantum numbers of the Higgs field, and why its squared mass is negative. In addition, the squared-mass of a fundamental scalar field receives quadratically divergent radiative corrections, hence suffers from the “hierarchy problem” if the cutoff scale is much higher than the weak scale. This problem can be avoided if the Higgs is a composite object rather than a fundamental field, and cease to be a dynamical degree of freedom not much above the weak scale. In fact, even without the Higgs field, the electroweak symmetry would still be broken by the quark-anti-quark condensate when QCD becomes strong at low energies. The breaking scale is three orders of magnitude too small. Nevertheless, it shows that a composite Higgs condensate can arise if there is strong interaction at the TeV scale.

Gauge interactions in more than four dimensions are non-renormalizable and rapidly become strong at high energies. Therefore, the SM gauge interactions can become strong at the TeV scale and be responsible for forming the composite Higgs if they propagate in extra dimensions of the  $\text{TeV}^{-1}$  size. Furthermore, the constituents of the composite Higgs field can naturally be the SM top quark and its Kaluza-Klein (KK) excitations.<sup>1,2</sup> The model is minimal in the sense that no new fields or interactions beyond the observed in the Standard Model are needed for the EWSB. It can also give powerful predictions which are in good agreement with the experimental results. We will discuss an example in the following.

Consider a one generation model in which the SM gauge fields and the third generation fermions live in six dimensions, with two of the six dimensions compactified at a scale  $M_c \sim \text{TeV}^{-1}$ . (Inclusion of the first two generations will be

discussed later.) The theory is non-renormalizable hence needs a physical cutoff  $M_s$ . A possible candidate is the scale of quantum gravity, which is determined by the sizes of the extra dimensions accessible to the gravitons.<sup>3,4</sup> In six dimensions, there exist four-component chiral fermions. We assign  $SU(2)_W$  doublets with positive chirality,  $\mathcal{Q}_+$ ,  $\mathcal{L}_+$ , and  $SU(2)_W$  singlets with negative chirality,  $\mathcal{U}_-$ ,  $\mathcal{D}_-$ ,  $\mathcal{E}_-$ . Each fermion contains both left- and right-handed two-component spinors when reduced to four dimensions. We impose an orbifold projection such that the right-handed components of  $\mathcal{Q}_+$ ,  $\mathcal{L}_+$ , and left-handed components of  $\mathcal{U}_-$ ,  $\mathcal{D}_-$ ,  $\mathcal{E}_-$ , are odd under the orbifold  $\mathbf{Z}_2$  symmetry and therefore the corresponding zero modes are projected out. As a result, the zero-mode fermions are two-component four-dimensional quarks and leptons:  $\mathcal{Q}_+^{(0)} \equiv (t, b)_L$ ,  $\mathcal{U}_-^{(0)} \equiv t_R$ ,  $\mathcal{D}_-^{(0)} \equiv b_R$ ,  $\mathcal{L}_+^{(0)} \equiv (\nu_\tau, \tau)_L$ ,  $\mathcal{E}_-^{(0)} \equiv \tau_R$ .

At the cutoff scale, the SM gauge interactions are strong and will produce bound states. The squared-mass of a scalar bound state has quadratic dependence on the cutoff, and can become much smaller than the cutoff scale or even negative if the coupling is sufficiently strong. Using the one-gauge-boson-exchange approximation, one finds in general among possible scalar bound states,  $H_{\mathcal{U}} = \overline{\mathcal{Q}}_+ \mathcal{U}_-$ , which has the correct quantum number to be the Higgs field, is the most attractive channel. Therefore it is most likely to acquire a negative squared-mass to break the electroweak symmetry. The composite Higgs is expected to have large coupling to its constituents, so it not only predicts the correct Higgs quantum number, but also a heavy up-type quark (top quark). The  $H_{\mathcal{D}} = \overline{\mathcal{Q}}_+ \mathcal{D}_-$  channel is also quite strongly bound while the other channels are not sufficiently strong to produce light bound states. The low-energy theory below  $M_c$  is expected to be a two-Higgs-doublet model.

Compared with the usual four-dimensional dynamical EWSB models, the higher-dimensional model has the advantage that the binding force can be the SM gauge interactions themselves, without the need of introducing new strong interactions. In addition, it also gives a prediction of the top quark mass naturally in the right range. In the minimal four-dimensional top quark condensate model, the top quark is too heavy,  $\sim 600$  GeV, if the compositeness scale is in the TeV range.<sup>5</sup> The correct top mass can be obtained if some additional vector-like quarks which also participate in the electroweak symmetry breaking.<sup>6</sup> They are naturally provided by the KK excitations of the top quark in a theory with extra dimensions. Another way of understanding of the top Yukawa coupling being  $\sim 1$  instead of the strong coupling value  $\sim 4\pi$  is that (the zero mode of) the top quark coupling receives a volume dilution factor because it propagates in extra dimensions. In fact, the top quark mass can be predicted quite insensitively to the cutoff because of the infrared fixed point behavior of the renormalization group (RG) evaluation. The infrared fixed point is rapidly approached due to the power-law running in extra-dimensional theories,<sup>7</sup> even though the cutoff scale is not much higher than the weak scale. Similarly, the Higgs self-coupling also receives the extra-dimensional volume suppression. As a result, the physical Higgs boson is relatively light,  $\sim 200$  GeV, in contrast with the usual dynamical EWSB models. It is also governed by the infrared

fixed point of the RG equations. The numerical predictions of the top quark mass and the Higgs boson mass are shown in Fig. 1.

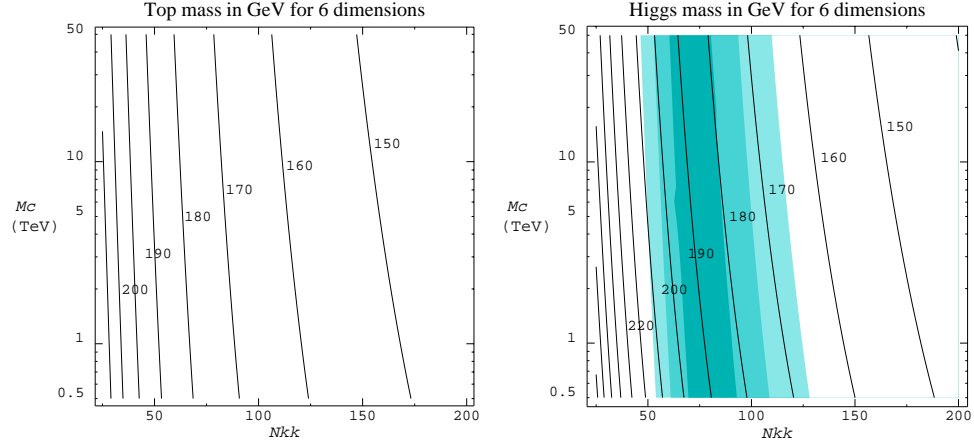


Fig. 1. The top quark mass (left) and the Higgs boson mass (right) as functions of the number of KK excitations,  $N_{KK}$ , and the compactification scale  $M_c$  in the six-dimensional theory. The shaded area in the Higgs boson mass prediction corresponds to the top quark mass lying within  $3\sigma$  of the experimental value,  $174.3 \pm 5.1$  GeV.

In more general models, there may be other light bound states which could be observed in the upcoming collider experiments in addition to the Higgs bosons. The possible light bound states depend on the model. For example, in the eight-dimensional model, there is a strongly bound state  $\overline{Q}Q^c$  transforming like the right-handed bottom quark under the SM gauge group.<sup>2</sup> Inclusion of the first two generations may also introduce more bound states. If the first two generations are localized in four dimensions, they can form four-dimensional bound states, though their binding strength may be smaller because they have no contribution from the extra components of the gauge fields. If all three generations of fermions live in the bulk, then we need to introduce explicit flavor-breaking interactions from the cutoff scale to distinguish them. The flavor-breaking interactions should enhance the third generation channels relative to the first two generation channels so that only the composite Higgs field from the third generation top quark have a negative squared-mass and is responsible for the EWSB. These flavor-breaking interactions can also give masses to the other light fermions.

1. H.-C. Cheng, B. A. Dobrescu and C. T. Hill, Nucl. Phys. **B589**, 249 (2000).
2. N. Arkani-Hamed, H.-C. Cheng, B. A. Dobrescu and L. J. Hall, Phys. Rev. **D62**, 096006 (2000).
3. N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. **B429**, 263 (1998).
4. L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999).
5. W.A. Bardeen, C.T. Hill and M. Lindner, Phys. Rev. **D41**, 1647 (1990).
6. R.S. Chivukula, B.A. Dobrescu, H. Georgi and C.T. Hill, Phys. Rev. **D59**, 075003 (1999).
7. K.R. Dienes, E. Dudas and T. Gherghetta, Phys. Lett. **B436**, 55 (1998).